NASA TTF-9589

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Translation of "Problema obosnovaniya dopustimykh doz ioniziruyushchey radiatsii dlya chlenov ekipazha kosmicheskikh korabley".
Paper Presented at the XVI International Astronautical Congress, Athens, September 13-18, 1965.

GPO PRICE $ _____

CSFTI PRICE(S) $ _____

Hard copy (HC) $1.00

Microfiche (MF) .50

ff 653 July 65

N65 35524

(ACCESSION NUMBER) 25 (PAGES) (NASA CR OR TMX OR AD NUMBER)

(THRU) 1 (CODE) 04 (CATEGORY)

FACILITY FORM 602

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON D.C. OCTOBER 1965

# THE PROBLEM OF ESTABLISHING TOLERABLE DOSES OF IONIZING RADIATION FOR CREW MEMBERS OF SPACECRAFTS

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ABSTRACT

Based on clinical findings, the authors determine that the critical radiation dose during short space flights is 125 r. A tentative estimate of 100 rem/year is made for long flights.

Author

One of the factors which inevitably affect man in space flight /1* is known to be ionizing radiation. The radiation environment during such flights is comprised of three main sources -- galactic cosmic radiation (GCR), the earth's radiation belts, and the radiation accompanying solar flares.

Modern information indicates that the GCR dose rate in interplanetary space is 34-35 mrad per day (Ref. 1). The radiation dose from the earth's radiation belts may, according to existing data (Ref. 2), be 3-5 rad when traversing these belts behind a shielding of 10 g/cm$^2$. The radiation danger from solar flares depends on the cycle of solar activity and the flight duration. The intensity of the corpuscular streams generated during individual solar flares may differ by several orders. Latest data (Ref. 3) indicate that the

* Note: Numbers in the margin indicate pagination in the original foreign text.

protons from solar flares can create an average tissue dose of up to 35 rad behind a shielding of 10 g/cm$^2$.

In the light of these findings, astronauts shielded by 10 g/cm$^2$, when flying the earth-moon-earth route for an average period of 10-15 days, may be subjected to 4-40 rad doses of cosmic radiation, depending on solar activity (Refs. 4, 5, 6). During flights to other planets in the solar system, the total absorbed dose of GCR will also increase in proportion to flight duration. Under conditions of protracted flight, moreover, the possibility also becomes greater that the astronauts /2 will be irradiated by corpuscular streams from several solar flares differing in intensity.

Calculations thus show that spaceship crews during space flights may be affected by cosmic radiation in dosages exceeding the existing standards for vocational exposure. For technical reasons it is impossible (Ref. 7) to set up anti-cosmic radiation shielding on the spaceship to reduce the dosages to levels recommended by the International Commission on Radiation Protection (Ref. 8).

In view of the above statements, and also in view of the fact that the group of people professionally engaged as astronauts is very limited, we deem it advisable to introduce a special classification of irradiation levels which can be used to evaluate the radiation danger in long and short flights.

It is our opinion (Ref. 9) that three dosage categories must be provided:

- the tolerable dose (TD),

- the dosage of justifiable risk (JRD), and

- the critical dose (CD).

TD is the dosage of ionizing radiation which in the light of modern findings causes an individual no perceptible somatic damage during his entire life.

JRD is the dosage of ionizing radiation which may cause merely individual cases of poorly-expressed clinical manifestations of radiation injury with the total exclusion of fatal results.

CD is the dosage of ionizing radiation which may lead to clear clinical symptoms of radiation injury, but without fatal results.

The basis of the recommended dosages must take into account the specific radiation environment depending on space flight duration.

We propose tentatively to assume that the effect of cosmic radiation (from GCR, traversing the earth's radiation belts, and solar flares) during short flights is a single exposure effect, although the irradiation may last several days. Here the expected effect is deliberately heightened, since the recuperative processes during protracted or fractionated action will be more pronounced. This assumption may therefore be considered quite feasible, all the more so because it is to the advantage of the astronaut.

In protracted flights, irradiation is assumed to be chronic, both from GCR and from the repeated acute effects of solar flare protons.

Proceeding from the above reasoning, it is advantageous to examine separately the bases for tolerable doses of ionizing radiation during /3 long and short space flights.

Tolerable doses during short space flights may be estimated by

using observations of individuals who have been exposed to irradiation in accidents and atomic explosions, as well as those therapeutically irradiated.

Solar flare radiation, which sets up dosages on the order of tens of rads behind the actual shielding device, is the main danger in flights of short duration. Therefore, we consider it advisable mainly to use data on the clinical observations of over-all fractional therapeutic irradiation to establish the tolerable doses. The value of the research data lies in the fact that the use of clinical irradiation makes it possible, first, to form a preliminary estimate of the state of the irradiated individuals and, second, to evaluate precisely the radiation dose they receive, which corresponds in some degree to the dosages which a shielded astronaut may get during a solar flare.

We had the opportunity of observing 97 individuals, chiefly women, subjected to subtotal irradiation either for prophylaxis after radial operation for second or third stage breast cancer, or for a metastatic process, also principally breast cancer (Refs. 10, 11, 12). We used this method of irradiation because of the great amount of experience with total irradiation in oncological practice (Refs. 13, 14, 15, etc.). The group of examinees was from 30 to 60 years old, the majority 40 to 50 years of age. Before irradiation the patients were for the most part in a satisfactory state, making radiation therapy under ambulatory conditions possible. All the examinees were irradiated in an RUM-3 X-ray machine at 180 kw, 15 ma, filter 0.5 mm Cu + 1.0 mm Al; distance from source to center of body 120 cm; rate of dose 3.6 - 5.0 r

per min. The upper and lower portions of the body, front and back, were irradiated alternately. The single dose was 25 r daily or, in individual cases, every other day up to total doses of 100-300 r.

The patients' reactions to radiation were evaluated for total body condition and dynamics of peripheral blood changes. The clinical symptoms of the primary reaction were evaluated according to three degrees of severity:

- first degree reaction -- general reaction symptoms isolated and slightly marked (slight weakness, headache, nausea, anorexia, slight vertigo, etc.);
- second degree reaction -- symptoms leading to a certain reduction in capacity for work (general weakness, persistent nausea, single vomiting, pronounced anorexia, olfactory and gustatory perversions, headache, vertigo, etc.);
- third degree reaction -- symptoms causing marked reduction in capacity for work (severe general weakness, anorexia, pronounced nausea, repeated emesis, apathy, rise in body temperature, chills, marked perversion of taste and smell, severe headache, drastic vertigo). /5

The table below gives the observational results in degrees of severity of primary reaction symptoms depending on radiation dosage. These data indicate that most of the individuals tolerated 25 and 50 r radiation doses well (81.6% and 66.7%, respectively). With a further increase in total dose, the total number of individuals without primary reaction to irradiation was observed to decrease. With a 125 r dose, only 35.8% of the examinees were without clinical symptoms of total reaction.

FREQUENCY OF OCCURRENCE AND DEGREE OF SEVERITY OF GENERAL REACTION IN ITS DEPENDENCE ON DOSAGE

| Dose r* | Total number of patients | Reaction | | | | | | Degree of Evidence of Clinical Symptoms | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | No Clinical Symptoms | | | Pronounced | | | 1st Degree | | | 2nd Degree | | | 3rd Degree | | |
| | | No. of patients | % | Confidence Range | No. of patients | % | Confidence Range | No. of patients | % | Confidence Range | No. of patients | % | Confidence Range | No. of patients | % | Confidence Range |
| 25 | 97 | 79 | 86,1 | 72,6—88,7 | 18 | 18,4 | 11.3—27.4; | 10 | 10,2 | 5,0—19,6 | 6 | 6,1 | 2,6—14,5 | 2 | 2,1 | 0,3—8,0 |
| 50 | 69 | 47 | 66,7 | 55,8—78,6 | 22 | 33,3 | 20.9—43.7; | 15 | 21,7 | 14,0—36,2 | 6 | 8,8 | 4,2—22,7 | 1 | 1,4 | 0,1—10,0 |
| 75 | 66 | 35 | 53,1 | 38,4—63,0 | 31 | 49,6 | 34.3—59.6; | 26 | 39,3 | 30,0—55,9 | 5 | 7,7 | 4,2—26,8 | — | — | — |
| 100 | 61 | 29 | 47,6 | 34,0—59,9 | 32 | 52,4 | 39.1—65.3; | 22 | 36,0 | 29,3—57,7 | 10 | 16,3 | 13,0—42,1 | — | — | — |
| 125 | 42 | 15 | 35,7 | 21,6—52,0 | 27 | 64,3 | 48.0—78.4; | 18 | 42,0 | 36,3—71,9 | 7 | 16,6 | 13,9—54,9 | 2 | 4,6 | 1,5—36,0 |
| 150 | 40 | 17 | 42,5 | 27,0—59,1 | 23 | 57,5 | 40.9—73.0; | 16 | 40,0 | 30,8—66,5 | 4 | 10,0 | 5,4—41,9 | 3 | 7,5 | 3,2—37,0 |
| 175 | 34 | 17 | 50,0 | 32,4—67,6 | 17 | 50,0 | 32.4—67.6; | 10 | 29,4 | 19,4—57,7 | 5 | 14,7 | 7,8—45,3 | 2 | 5,9 | 1,3—33,0 |
| 200 | 32 | 16 | 50,0 | 31,9—68,1 | 16 | 50,0 | 31.9—68.1 | 12 | 37,5 | 24,5—62,8 | 3 | 9,4 | 3,4—39,6 | 1 | 3,1 | 0,1—28,0 |
| 225 | 15 | 10 | 66,7 | | 5 | 33,3 | | 5 | | | | | | | | |
| 250 | 10 | 6 | 60,0 | | 4 | 40,0 | | | | | | | | | | |
| 300 | 7 | 4 | 57,2 | | 3 | 42,8 | | | | | | | | | | |

* Patients irradiated repeatedly at 25 r, as a rule, every day. We have estimated total effect as a single irradiation.

A statistically-reliable pattern of increase in rate of reaction onset with a total dosage of 125 r is evident, as well as the subsequent stabilization of the clinical symptoms between doses from 125 to 200 r (such a stabilization is probably associated with the feasibility of applying such total dosages to patients resistant to radiation).

In most individuals the primary reaction was poorly-expressed, and we evaluated it as a 1st degree reaction. The pattern of increase in 1st and 2nd degree reactions. depending on total irradiation dose, is approximately the same with a maximum at dose 100-125 r. The 3rd degree reaction was chiefly manifested when total dosage reached 125 r with a maximum at 150 r.

Ananalysis of the individual symptoms, as well as of the reaction as a whole, demonstrated a gradual increase in frequency of appearance of such frequently-encountered symptoms as general debility, disturbance of appetite, and nausea. A marked increase in these symptoms was noted after irradiation with a total dose of 75 r, with a maximum increase from 125 to 150 r. The increases in cases of emesis in patients irradiated with total doses of 125-175 r is noteworthy.

We observed no clear relationship between total reaction and changes in the peripheral blood. The maximum decrease in leukocyte count was noted at periods from 35 to 55 days, regardless of the total dosages received in the 200-400 r range, or of the degree to which the over-all reaction was expressed.

We must, however, draw attention to individual cases where the 1st and 2nd degree primary reaction occurred as a result of dosages

of 25 and 50 r. In seven of the 97 individuals, after the first irradiation we observed pronounced general debility, vertigo, headache, anorexia, and severe nausea, and in three cases even vomiting. It is true that we could not confidently assert that the deterioration was connected only with radiation effects in the patient, since before then he had had pronounced vegetative dystonia. Based on clinical /6 indices, in four cases repeated irradiation was nevertheless tried at different time intervals (from one day to six months), and all four patients again displayed a marked reaction similar to that of the first irradiation, or more severe. In addition to the seven above-considered observations, a 2nd degree reaction also occurred in three individuals after a second irradiation (total radiation dose, 50 r). Thus, in ten patients we observed a primary reaction, which became evident very rapidly, to the effect of radiation in a 25-50 r dosage.

The proof that in the patients of this group the reaction was to irradiation, and not a deterioration connected with the basic disease, lies first of all in the fact that, after stopping the irradiation, all the mentioned symptoms disappeared, and, second, repeated radiation action again brought out the same symptoms as after the first irradiation. From this group we obtained a certain increase in frequency of 2nd and 3rd degree reactions to 25 and 50 r dosages. In contrast to the group of patients with marked reaction to the effect of radiation, another group (14 patients) tolerated irradiation without any symptoms of primary reaction, or else with insignificant manifestations thereof. We had the opportunity of completely carrying out the irradiation process on these patients, and took the total dosage

up to 200-400 r.

Our observations with irradiation doses on the order of 25-50 r, as well as isolated cases of early general reaction in individuals described by Miller (Ref. 16) and Medinger (Ref. 17), indicate that some of them have a very high sensitivity to radiation, and point out the need for special selection of candidates for space flights. This is also corroborated by the findings of experimental research (Refs. 18, 19). As indicated before, however, we must make allowances for that fact that perfectly healthy individuals who have undergone specific training are rigorously selected for space flights, while in the radiological clinic people are subjected to radiation chiefly because of malignant neoplasms or after major operations and different types of treatment, which could by no means fail to be reflected in the general condition and reactivity of the body.

Thus, in evaluating frequency and degree to which a primary reaction is manifested as a whole, we must note that under our conditions of fractionated irradiation most of the patients either exhibited no reaction, or this reaction was not significant (1st degree of severity) on all the dosage levels which we traced. Even with total doses of 125 r and above, about 80% of the individuals can be assigned to this group. Medinger obtained similar data (Ref. 17).

Other data for establishing the tolerable radiation levels under short space flight conditions may include clinical observations of the reaction of individuals to a single total irradiation in large doses (reactor damage with more or less uniform irradiation, atomic explosion, //

irradiation with large doses for therapeutic reasons). Depending on the degree of clinical symptoms and the irradiation dose level, we divided all the existing observations into two groups.

To the first group, based on the classification of G. D. Baysogolov and A. K. Gus'kova (Ref. 20), we assigned individuals whose irradiation dose did not exceed 250 rem. Such are cases 6 and 7 (Ref. 21), cases 1 and 2 (Ref. 22), case 5 (Ref. 23), the group of atomic explosion victims on Rangelap Atoll with a dose of 172 r (Ref. 24), case 11 (Ref. 25), and the 30 cases in (Ref. 16).

To the second group we assigned the observations of Soviet investigators (Refs. 27, 28, 29), as well as observations 2, 3, 4 of Andrews et al. (Ref. 23), and observations of Hiroshima and Nagasaki victims (Ref. 50). The irradiation dosage of most people in these groups was 250-400 rem.

Analysis of observations of the first group shows that with irradiation in doses of 100-250 r most individuals develop a primary reaction lasting 1-3 days. In the first reaction, moreover, the predominant signs are those of general functional disturbances combined with superficial tissue damage (moderate reduction or red marrow cells, lymphopenia, leukopenia, thrombocytopenia).

Typical of the second group of individuals was a marked primary reaction lasting 2-3 days with evidence of definite tissue damage (perceptible decrease in number of young marrow cells, marked leukopenia, lymphopenia, and thrombocytopenia), with subsequent pronounced clinical signs of radiation sickness.

When estimating radiation TD, JRD, and CD for short space flights,

we must take into consideration a number of features which may be neglected in other situations. In particular, the possible development of a primary reaction to the effect of radiation is of great importance in determining radiation danger during space flights, since the manifestation of the 2nd, and particularly the 3rd degree reaction, can involve serious consequences. From the material we have presented, it follows that with a single irradiation of 25 r individual cases of 2nd - 3rd degree primary reaction are detected, and therefore such a dose cannot be adopted as tolerable under short flight conditions. We believe it advisable to assume the tolerable dose to be 15 rems (Ref. 9). It is known that this dose does not result in somatic effects (Refs. 31, 32), while minimum disturbance in hematological shifts are determined only from statistical processing of the results of blood counts on a great many irradiated individuals (Refs, 32, 33, 34).

According to our data, only 33.3% of the cases with a 50 r dose show any degree of primary reaction, and only in isolated cases is it /8 possible for 3rd degree reaction to appear. No stable somatic changes occur with this dosage, and only blood changes are possible (Refs. 8, 31, 32, 33). A fatal result with 50 r irradiation is completely excluded. In view of the above, we may determine the JRD to be a 50 rem dose.

A maximum increase in frequency with which primary reaction appears on the basis of our research, i.e., in fractionated irradiation, is determined with the 125 r dose (64 %). Here the number of cases with 2nd and 3rd degree reactions rises to 21.3%. Twelve

patients showed a pronounced primary reaction accompanied by vomiting (Ref. 34) from the effect of a single 125-175 r dose (Ref. 16). Comparing our findings with those of Gerstner (Ref. 26), we find that a single treatment gives a sharper increase in frequency of pronounced primary reaction as the dosage increases than does fractionated irradiation.

Proceeding from these findings and taking into consideration the rigorous selection and training of astronauts during preparations for space flight, we may consider their critical dose during short flights to be 125 r (Ref. 9). A further increase in the dose may lead to development of pronounced radiation sickness requiring therapeutic and prophylactic measures.

Considerably more complex is the problem of establishing standards for protracted space flights. On the earth-Mars-earth trajectory, the flight time will evidently be 2.5 to 3 years (Refs. 35, 56). In this period the total amount of GCR radiation may be 69-91 rem per year, or 174-274 rem for the flight (Refs. 2, 3). Solar flare radiation may increase the per capita dose, even behind a shielding of 25 $g/cm^2$, to approximately 550 rem per year (Ref. 37).

In view of the flight duration (2.5-3 years), the effect of GCR under these conditions may be assessed as chronic. It follows from this that if the dosage estimate in short flights must take into consideration the primary reaction to irradiation, in longer flights the manifestation of the effects of radiation at more remote periods must be borne in mind. Therefore, the study of data on prolonged radiation action under vocational and experimental conditions takes on great

significance.

Our personal experience (Ref. 37), the data of other investigations (Refs. 39, 40, 41), and analysis of numerous materials abstracted by the International Commission on Radiological Protection make it possible to arrive at a clinical basis for tolerable levels of radiation with respect to prolonged cosmic flights.

To provide a clinical characterization of chronic radiation /9 effects, we may consider the following grouping of the extant observations based on the level of irradiation doses.

First group. Individuals operating reactors (Ref. 42), accelerators (Refs. 43, 44, 45, 46), and doing neutron logging (Refs. 47, 48), as well as X-ray operators beginning work in the last 3-5 years, and most persons using isotopes in scientific research institutes. The total irradiation doses, both calculated and measured, did not exceed 30-50 rem, depending on time on the job (6-7 years), and most often were 15-30 rem.

On the basis of clinical indices, these persons did not display any particular differences as compared with the findings in control groups (Ref. 49, 50, 51, 52, 53, 54, 55, 56, 57). Only a few changes of a functional nature in individual organs and systems during special clinico-physiological investigations were determined. These changes did not impair working capacity, did not progress, and even smoothed out during protracted dynamic observation.

Second group. Persons having worked a long time on the job (10-15 years), X-ray operators (in the first years of their work, the

extreme amount of vocational radiation load was 15 rem per year), restricted groups of radiographers (Refs. 49, 58), and workers in certain experimental installations. These individuals were not uniformly subjected to irradiation in time (2/3 to 4/5 of the total 50-150 r dose was received in the first year of work). This group more regularly displays vegetative-vascular instability, in some cases with clinical symptoms of neuro-circulatory dystonia of the hypotonic type and hypofunction of the secretory system of the stomach. As the upper dose range is approached, chronic 1st degree radiation sickness develops in individual cases. The changes occur slowly, and regress for 2-5 years after cessation of irradiation or reduction in its level to the extreme tolerable level adopted.

Third group. Chiefly X-ray operators with 20 or more years on the job, or persons who in former years compiled radium preparations and luminous compounds containing radium. This is the smallest group. The total dosage of X-ray or gamma-radiation is 150-400 r and even 1000-2000 r (Ref. 59). The irradiation rate for these persons could in some years have exceeded the extreme tolerable dose by 10 to 30 times. Formation of a clinical syndrome of chronic 1st degree (more rarely 2nd degree) radiation sickness is observed (Refs. 20, 38, 39, 49). The periods at which clinical symptoms appear are clearly correlated with the irradiation rate during determined years (wilful infraction of standards and work rules). This group includes the overwhelming majority of cases in which far-removed effects of radiation action and individual unfavorable results appear. According to our observations,

however, even the X-ray operators with a long time on the job (third group), whose total doses in the last few years have increased insignificantly, display perceptible improvement in their general /10 state, and their clinical indices approximate their original values. It should be stressed that for the last observation period only 1% of the cases evidenced changes of a vocational nature (Ref. 60).

It thus follows from the above data that a total irradiation dose not exceeding 100-150 r practically eliminates the opportunity for the occurrence of a developed syndrome of chronic radiation sickness in early periods (from one to three years from moment of irradiation). If the radiation syndrome occurs, significant regenerative-adaptational processes are possible on cessation of the doses, even with individuals with rather large total doses (150-400 r). It is the opinion of A. K. Gus'kova (Ref. 38) and B. Rajewsky (Ref. 33) that a 70-100 r dose is below the danger level for immediate somatic effects. After irradiation in this dosage range, only light clinical symptoms are possible which are characteristic of chronic radiation sickness in the most sensitive individuals.

Of definite interest for the evaluation of radiation changes in prolonged space flights are the experimental findings on chronic irradiation of animals, since under experimental conditions the amounts of ionizing radiation doses may be more accurately estimated, and the ensuing biological effects more clearly followed. Of particular value, we think, are the data of experiments giving findings on the effects which may develop when crews are irradiated with doses corresponding

to the background GCR.

An analysis of the results of a number of experiments using mice, rats, and dogs irradiated for six months, a year, and two and a half years with doses of 0.2 - 0.5 r per day has shown that the experimental animals develop definite changes during these periods - impairment of hemopoiesis (change in the numerical ratio of neutrophils and lymphocytes, leukopenia, thrombocytopenia, etc. in a number of cases) (Refs. 61, 62, 63, 64, 65, 66); reduction of phagocytic activity, oxygen capacity of the blood, and catalase index (Ref. 65); development of disturbances in the reproductive system, appearing as reduced spermary weight index, decrease in number of spermatogonia, and aspermia (Refs. 61, 62, 65). Animals subjected to chronic irradiation may subsequently, however, be expected to have more frequent tumors and a certain decrease in lifespan (Ref. 67).

A decrease of one order of magnitude in the radiation dosages under similar irradiation conditions either caused less-marked changes in these processes (Refs. 64, 68, 69, 70), or gave rise to a more or less pronounced effect of so-called "stimulation". The latter was manifested in a certain increase in the relative number of leukocytes,/11 an increase in the number of spermatogonia, and in a certain lengthening of the animals' lifespan (Refs. 65, 67, 68). A rise of one order of magnitude in the daily and total radiation doses, however, caused earlier development and more extensive manifestation of the indicated hemopoietic reproductive, and other symptomatic disturbances (Refs. 71, 72, 73).

On the basis of existing knowledge on chronic irradiation both of human beings and of animals, we have a right to assume that chronic irradiation up to a total dosage of 100 rem per year for three years neither has fatal results, nor essentially impairs the working capacity of the spaceship crew during the entire flight. This level of irradiation may be regarded as the dose of justified risk for astronauts in the first long space flights. However, in view of the possibility of far-removed consequences and the relatively short period of clinical observations up to the present, the 100 rem per year dose may be considered to be merely tentative.

Special research is required to form a definitive opinion on the magnitude of tolerable radiation levels in flights to Mars and other distant planets. This research must be aimed at defining more precisely the RBE* of all types of cosmic radiation, at studying the far-removed consequences of processes entailing the adaptation, compensation, and restoration of changes in the irradiated organism, and at investigating the combined effect of ionizing radiation and other factors under conditions of prolonged space flight.

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